IMPACT OF THE PARAMETERIZATION OF THE SOURCE POSITIONS ON THE FREE CORE NUTATION

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ABSTRACT. The positions of the radio sources in the ICRF3 catalog, representing the newest realization of the Celestial Reference Frame (CRF), are given as time invariant coordinate pairs. Failing to acknowledge systematics within the source positions leads to a deterioration in the quality of the frame, and thus in all derived variables, such as the Earth orientation parameters (EOP). A proven approach to overcome these shortcomings is to extend the parameterization of source positions using the multivariate adaptive regression splines (MARS). They allow a great deal of automation, by combining recursive partitioning and spline fitting in an optimal way. Here we present first results on the impact of the parameterization of the source positions on the EOP and the estimation of the free core nutation.

1. INTRODUCTION

The Earth's Free Core Nutation (FCN) is one of the free rotational modes of the Earth. It describes the retrograde motion due to the misalignment between the rotation axes of the mantle and the' liquid core (Smith 1977, Wahr 1981). It has a retrograde period of about 430 days, with an average amplitude of about 100 μas (Mathews 2002,Vondrak 2005, Lambert & Dehant 2007) relative to a space-fixed reference frame. A comprehensive description of the precession and nutation theory detailing also the FCN can be found in Dehant and Mathews (2015).

However, until this day no models can predict this free motion, as its excitation mechanism is not fully understood. Thus it is not included in the precession-nutation model IAU2000/2006 (Mathews et al. 2002, Capitaine et al. 2003) recommended by the IERS (International Earth Rotation Service) Conventions (Petit and Luzum, 2010). However, the IERS Conventions propose an empirical model based on the IERS EOP C04 series (that can be found at `http://ivsopar.obspm.fr/fcn/`) that provides one reference value for yearly amplitudes.

Geodetic VLBI is the only space geodetic technique that is capable of accurately observing the variation of the Earths rotation axis in space in terms of celestial pole offsets (CPO), and thus the therein contained FCN signal. It is based on the observation of extra-galactic radio sources, which realize the inertial International Celestial Reference System (ICRS). The accuracies in positions of these radio sources depend on their individual intrinsic structural variations (Charlot, 2002), however in ICRF3 (Charlot et al, in prep.) the sources are considered as time-invariant and point-like. Neglecting any deviation from this definition can lead to a deterioration of the nutation estimates as shown for instance by Feissel-Vernier et al. (2005). Extending the parameterization of the source coordinates as proposed in Karbon et al. (2016a,b) can mitigate such effects, mainly by eliminating systematics in the sources defining the datum, and thus stabilizing the frame. Further, the modeling of the systematics in the source positions, allows the introduction of sources into the datum definition, which were until then classified as too unstable.

This work follows up on these results and gives a first impression on the impact of the parameterization of the source positions on the FCN signal.

2. PARAMETERIZATION OF THE SOURCES

The MARS algorithm (Friedman, 1991) is a method for flexible regression modeling, and delivering continuous linear splines. As it can be fully automated, the large number of source coordinate time-series to be parameterized does not pose a problem. The model consists of a weighted sum of spline basis functions. The number of basis functions as well as the associated parameters (e.g. degree and knot locations) are determined automatically be the data using recursive partitioning. Here only an example of the results shall be given. For further information refer to the original publication by Friedman and to Karbon et al. (2016a,b).

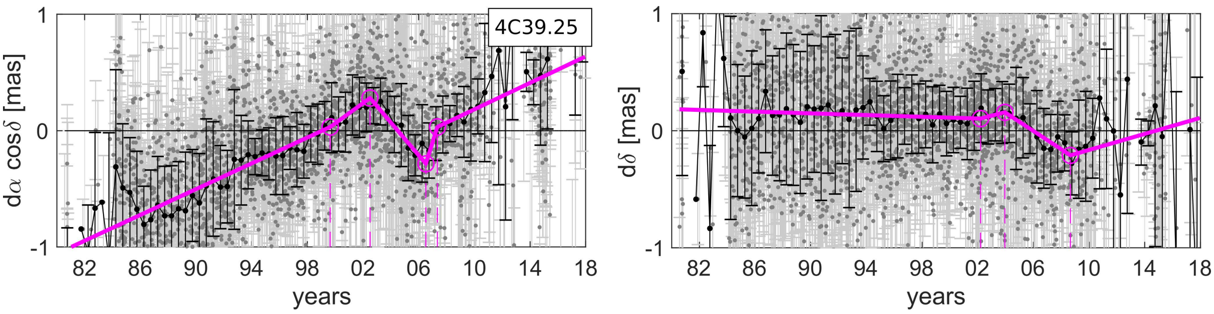

Figure 1: The estimates for former special handling source 4C39.25 with their error bars in gray and the semi-annual mean values in black. The estimated MARS spline is given in magenta.

Figure 1 shows the estimates of the source positions of the ICRF2 special handling source 4C39.25 in gray, overlaid with the magenta spline determined by MARS. It is an exceptionally well observed source, however, due to its instability it cannot contribute to the datum definition of the reference frame. As one can see, the spline follows to great extent the semi-annual mean values (black). Only where the estimates show larger uncertainties, the algorithm down-weights the positions considerably, thus the segmentation of the spline remains unaffected.

For all sources which are observed in more than 10 sessions, we estimated such splines. These splines are then introduced in the VLBI analysis software as corrections for the a-priori source positions taken from the ICRF3 catalog. Hence, where the instability of some sources prevented their inclusion in the datum definition, the extension of the coordinate model of these sources makes this now possible.

3. DATA AND PROCESSING

For our study we used more than 4500 sessions within 1980 and 2018, with station networks that encompass more than $10^{15}m^3$ to ensure a stable geometry, and hence a reliable estimation of the EOP. The geodetic data analysis is performed using the VLBI software package VieVS (Böhm et al., 2018), and following the conventions of the IERS. The modeling settings are chosen with respect to the routine single-session data analysis strategies of the International VLBI Service for Geodesy and Astrometry (IVS, Nothnagel et al., 2015). For the stacking of the normal equations we used our own stand-alone software.

As reference serves the solution (0) using the 303 ICRF3-defining sources for the datum definition (i.e. sets of sources which enter the no-net-rotation condition), and without additional parameterization for the sources. For the solutions applying the parameterization to the source positions, we defined 3 different datums. A map of the distribution of the used datum sources is shown on the left in Figure 2:

(I) all ICRF3 defining sources: 303,

(II) all ICRF3 defining sources except the 32 least observed ones, plus the 32 most observed special handling sources: 303,

(III) the 152 most observed sources in the northern and southern hemisphere, independent of classification: 304.

As can be seen on the left in Figure 2 the distribution of the ICRF3 defining sources (gray) improved significantly compared to ICRF2. However, the alternative datum definitions (magenta and black) still show larger numbers in the far south. Yet, the number of defining sources per sessions has not increased with ICRF3, especially the first decade of observations is still lacking. The alternative datum definitions can increase these numbers dramatically by 100% for (II) and almost 150% for (III). Over the entire time-span the increase w.r.t. ICRF3 is 30% and 50%, respectively.

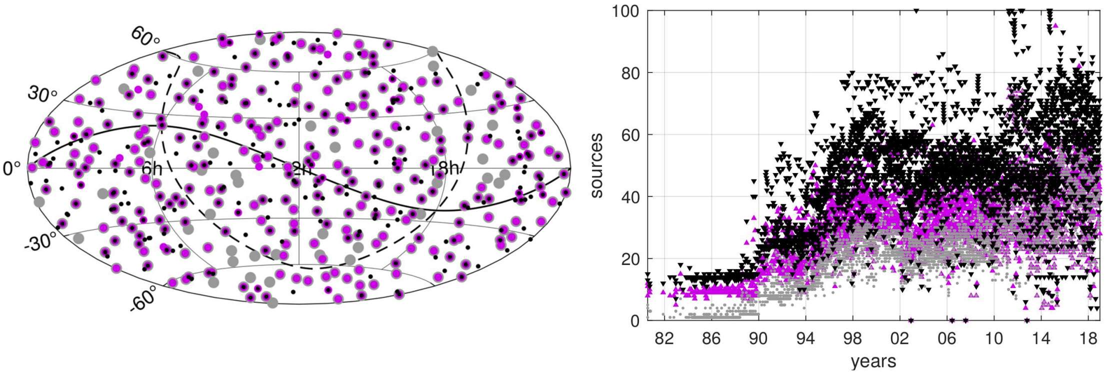

Figure 2: **left:** Datum definitions: ICRF3 in gray (I), (II) in magenta and (III) in black. **right:** number of datum sources per session.

4. QUICK-LOOK: CELESTIAL POLE OFFSETS

Using each datum definition, four sets of normal equations were generated, which were then stacked to generate four homogeneous time series of the CPO. Although the ICRF3 defining sources are much better distributed than they were in ICRF2, the increased number of them within the alternative datum definition has still a significant positive impact on the CPO. Figure 3 shows on the left exemplarily the estimates for dX and dY for the reference solution (0) in gray and solution (II) in magenta, to the a-priori the values given by IERS 14 C04. On the right we show the difference. (II) reduces the weighted RMS about 30%, and about 10% when neglecting the early data until 1995; same for solution (III).

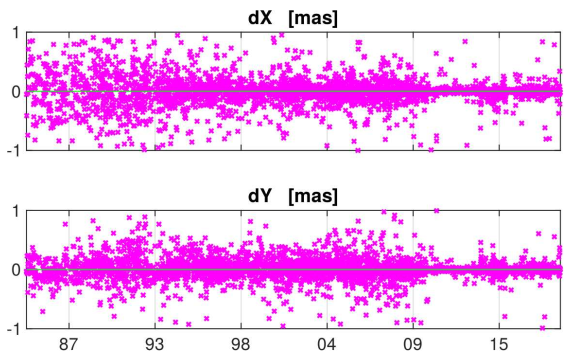

Figure 3: **D**ifference between the CPO residuals using (0) and (II).

5. EMPIRICAL MODEL OF FCN

Using the processing scheme presented in Chap. 3, we determined CPO time-series omitting the IERS-FCN model. Then we used the model described in Eq. 1 to generate our empirical FCN models.

$$\begin{aligned} X_{FCN} &= A_C \; cos(\sigma_{FCN} \cdot t) - A_S \; sin(\sigma_{FCN} \cdot t), \\ Y_{FCN} &= A_S \; cos(\sigma_{FCN} \cdot t) + A_C \; sin(\sigma_{FCN} \cdot t) \; . \end{aligned} \quad (1)$$

Based on the work of Belda et al, (2017) we chose as a-priori period 430 days and an averaging window of 400 days. The left plot in Figure 4 shows the various input time-series with the clear FCN-signature, and exemplarily one of the estimated FCN models. The right plot shows the residuals of the individual time series w.r.t. the respective model: (0) in grey, (I) in purple, (II) in magenta and (III) in black. In green we show the solution including the IERS FCN-model a-priori in the analysis. Although slight differences exist, none of the models outperforms any of the others. Looking at the statistics of the residuals, the solutions applying the source parameterization show slightly smaller values for the weighted RMS, whereas the IERS-model gives the smallest standard deviations.

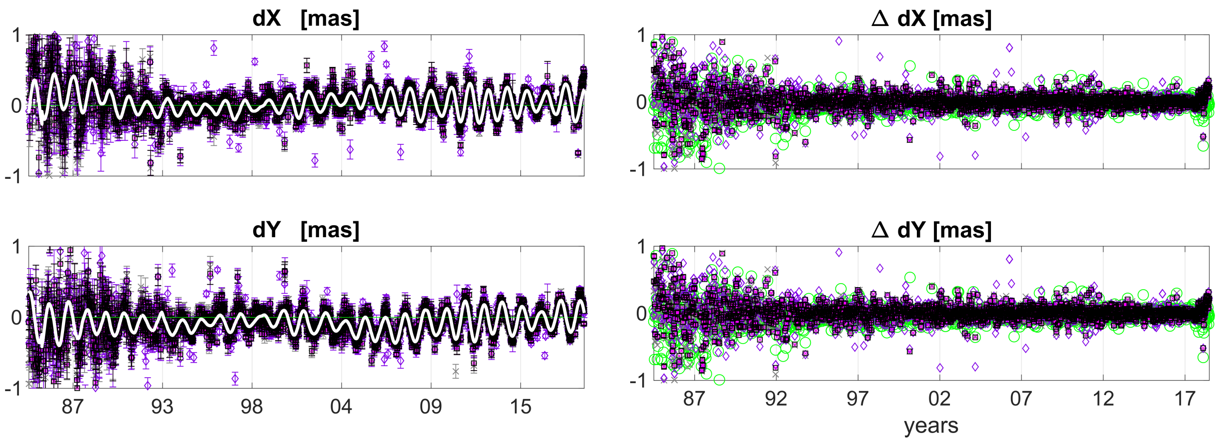

Figure 4: **left:** CPO time-series omitting FCN modeling and one model in white. **right:** Residuals w.r.t. models. **Color code:** (0) in gray, (I) in violet, (II) in magenta and (III) in black. The green solution applies the Lambert model a-priori.

We further compared our models with other established ones, i.e. the models by Lambert & Dehant (2007), Malkin (2013) and Belda et al. (2016). For this we restricted the time-span to 01.01.1990-31.12.2015 were all three models are available.

The left plot in Figure 5 shows the amplitudes and phases of the individual models. The smoothest curve is given by the Lambert-model (solid light-orange line) which uses the smallest number of constituents. The Malkin- (dashed light orange) and Belda-model (dashed dark orange) show more variability and better agreement with our models given in gray, violet, magenta and black (0-I-II-III). All our models are very close together in both amplitude and phase, (II) and (III) are practically identical. Only in the 90s the models diverge. These are the years where the parameterization and alternative datum definitions show the largest impact.

The right plot in Figure 5 shows the residual CPO w.r.t. the models. Besides a clear yearly signal remaining in all time-series, no clear differences in performance can be made out. Also looking at the statistics of these residuals shows again no clear differences. Our models perform overall better, however that is mostly due to the higher variability of the models. Again (II) and (III) show the smallest wRMS, whereas (0) gives the the smallest standard deviation.

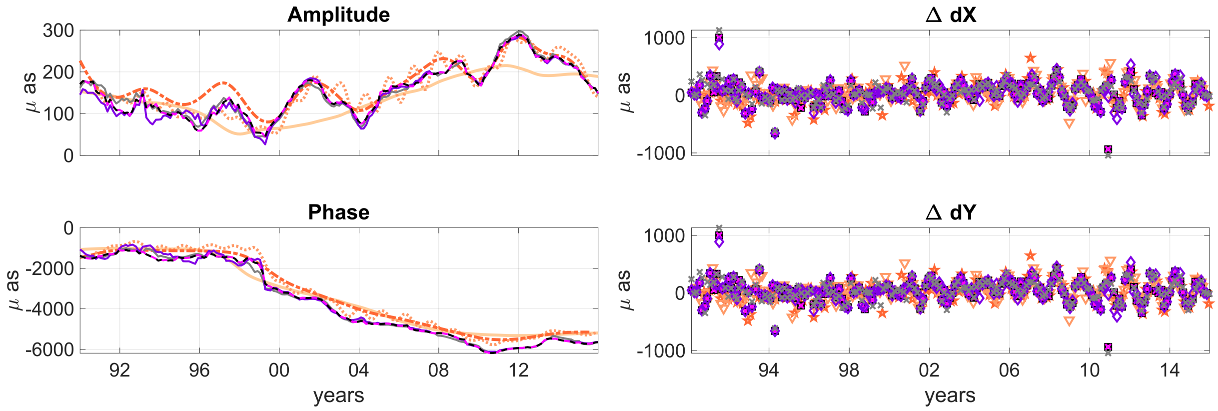

Figure 5: **left:** Amplitudes and phases of the FCN models. **right:** Residuals w.r.t. models. **Color code:** light upward triangle: Lambert, light downward triangle: Malkin, orange star: Belda, (I): violet, (II): magenta, (III): black.

6. CONCLUSIONS

The parameterization of source coordinates reduces the wRMS of CPO by 10-30%, also in view of the improved geometrical distribution of the ICRF3 defining sources. Our estimated FCN empirical models agree with established ones, however comparisons prove to be difficult, as no VLBI-independent solutions available. Further investigations need to be carried out.

7. REFERENCES

S. Belda, R. Heinkelmann, J.M. Ferrndiz, M. Karbon, T. Nilsson, and H. Schuh, 2017, "An improved empirical harmonic model of the celestial intermediate pole offsets from a global VLBI solution", AJ 154(4), p. 166.

Böhm, J., Böhm, S., Boisits, J., et al., 2018, "Vienna VLBI and satellite software (VieVS) for geodesy and astrometry", Publications of the Astronomical Society of the Pacific, 130(986), p. 044503.

N. Capitaine, P. T. Wallace, and J. Chapront, 2003, "Expressions for IAU 2000 precession quantities", A&A, 412, pp. 567–586,

P. Charlot, 2002, "Modeling radio source structure for improved VLBI data analysis", in N. R. Vandenberg and K. D. Baver, editors, International VLBI service for geodesy and astrometry 2002 general meeting proceedings, pp. 233–242. NASA/CP-2, pp. 233–24.

P. Charlot, C.S. Jacobs, D. Gordon, S. Lambert, A. de Witt, J. Böhm, A. Fey, R. Heinkelmann, E. Skurikhina, O. Titov, E. Arias, S. Bolotin, G. Bourda, C. Ma, Z. Malkin, A. Nothnagel, D. Mayer, D.S. MacMillan, T. Nilsson, R. Gaume, 2020, "The Third Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry", A&A , doi: 10.1051/0004-6361/202038368.

V. Dehant and P.M. Mathews., 2015, "Precession, Nutation and Wobble of the Earth", CAMBRIDGE UNIVERSITY PRESS, Cambridge, United Kingdom.

M. Feissel-Vernier, C. Ma, A. M. Gontier, and C. Barache, 2005, "Sidereal orientation of the Earth and stability of the VLBI celestial reference fram, A&A, 438, pp. 1141–1148

J. H. Friedman, 1991, "Multivariate Adaptive Regression Splines", The Annals of Statistics, 19(1), pp. 1–141.

M. Karbon, R. Heinkelmann, J. A. Mora-Diaz, M. Xu, T. Nilsson, and H. Schuh, 2016a, "The modeling of radio source time series as linear splines", In D. Behrend, editor, Proceedings of the Nineth IVS General Meeting: New Horizons with VGOS, Science Press, Johannesburg, South

Africa.
M. Karbon, R. Heinkelmann, J. A. Mora-Diaz, M. Xu, T. Nilsson, and H. Schuh, 2016b, "About the extension of the parametrization of the radio source coordinates in geodetic VLBI and its impact on the time series analysis", J. Geodesy .
S. B. Lambert and V. Dehant, 2007, "The Earth's core parameters as seen by the VLBI", A&A, 469, pp. 777–781.
Z. Malkin, 2013, "Free core nutation and geomagnetic jerks", Journal of Geodynamics 72, pp. 53–58.
P. M. Mathews, T. A. Herring, and B. A. Buffett, 2002, "Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior", J. Geophys. Res. (Solid Earth) 107(B4), ETG 31ETG 326.
Nothnagel, A., Alef, W., Amagai, J., et al., 2015, "The IVS data input to ITRF2014", GFZ Data Services, Helmoltz Centre, Potsdam, Germany
G. Petit and B. Luzum, editors, 2010, IERS Conventions (2010).
M.L. Smith, 1977, "Wobble and Nutation of the Earth", Geophysical Journal of the Royal Astronomical Society, 50(1), pp. 103–140.
J. Vondrák, R. Weber, and C. Ron, 2005, "Free Core Nutation: direct observations and resonance effects", A&A 444, pp. 297–303.
J.M. Wahr, 1981, "The forced nutations of an elliptical, rotating, elastic and oceanless Earth", Geophysical Journal of the Royal Astronomical Society, 64(3), pp. 705–727.